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Active and/or Passive Control of the Radiative and Reflective Properties of Uniform Panels: Part I. Theoretical Review and Development

by

G. Maidanik and J.Dickey

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CONTENTS

ABSTRACT

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INTRODUCTION

The control of the radiative and reflective properties of structural surfaces is the goal of many noise control engineering projects. The control devices that are utilized may be active and/or passive. In this paper an attempt is made to investigate the influence and effectiveness of some of these devices on the radiative and reflective properties of uniform panels. A uniform panel is chosen for the simplicity with which its radiative and reflective properties can be analyzed. [cf. Appendix A.] Compatibly, the passive control devices are in the form of thin uniform layers that are stratified to the basic panel and the active control devices are in the form of drives that are applied uniformly on the surfaces of some such layers. The properties of the passive mechanical layers and the active surface drives are specified in terms of lumped parameters rendering the investigation particularly simple. [cf. Appendix A.] Provided the limitations of the contrived simplicity are heeded, such investigations can be useful in furnishing phenomenological understandings of the benefits that the specified types of passive mechanical layers and active surface drives may yield. The analysis covered in this paper is conducted in this vein.

The uniformity of the basic panel, the passive mechanical layers, and the active surface drive makes it convenient to carry out the analysis in the $\{\underset{\sim}{k}, \omega\}$–domain, where $\underset{\sim}{k}$ is the Fourier conjugate of the spatial variable $\underset{\sim}{x}$ in the plane of the panel, and ω is the Fourier conjugate of the temporal variable t [1,2]. A sketch of the "basic panel + passive mechanical layers + active surface drives" that constitute the plane dynamic system, the fluids, on both sides, in which the dynamic system is immersed, and the external drives, is sketched in Figure 1. The velocity response vector $\underset{\sim}{V}(\underset{\sim}{k}, \omega)$ of that dynamic system, in situ, to an external drive vector $P_e(\underset{\sim}{k}, \omega)$ is given in terms of the surface impedance matrix $\underset{\approx}{Z}(\underset{\sim}{k}, \omega)$ in the form

$$\underset{\approx}{Z}(\underset{\sim}{k}, \omega)\, \underset{\sim}{V}(\underset{\sim}{k}, \omega) = \underset{\sim}{P_e}(\underset{\sim}{k}, \omega) - \underset{\sim}{P_a}(\underset{\sim}{k}, \omega) \quad , \tag{1}$$

$$\underset{\sim}{V} = \{V_j\} \quad ; \quad \underset{\sim}{P_e} = \{P_{ej}\} \quad ; \quad \underset{\sim}{P_a} = \{P_{aj}\} \quad , \tag{2}$$

$$\underset{\approx}{Z} = \Big((Z_{pj} + \sum_{j \neq i} Z_{cij})\, \delta_{ji} - Z_{cji}(1 - \delta_{ji})\Big) \quad , \tag{3a}$$

$$\underset{\approx}{Z_\alpha} = \Big((Z_{pj}\, [1 - \delta_{j\alpha}] + \sum_{j \neq i} Z_{cij})\, \delta_{ji} - Z_{cji}(1 - \delta_{ji})\Big) \quad , \tag{3b}$$

$$Z_{p\alpha}(\underset{\sim}{k}, \omega) = (\rho_\alpha \omega / k_{z\alpha}) \qquad ; \qquad \alpha = 1 \text{ or } N \quad ;$$

$$k_{z\alpha}(\underset{\sim}{k}, \omega) = [(\omega/c_\alpha)^2 - k^2]^{1/2}\, U[(\omega/c_\alpha)^2 - k^2] - i\, [k^2 - (\omega/c_\alpha)^2]^{1/2}\, U[k^2 - (\omega/c_\alpha)^2] \quad , \tag{4}$$

where the active surface drive vector is designated $\underset{\sim}{P_a}$, the (α)th fluid; $\alpha = 1$ or N, is defined by the density ρ_α and the speed of sound c_α; the fluid $\alpha = 1$ is atop the plane and $\alpha = N$ is below the plane of the basic panel [1,2]. Equation (1) makes it clear that, in whole or in part, the passive and the active devices can be conceptually and analytically interchanged. The whole or a part of the active surface drives $\underset{\sim}{P_a}(\underset{\sim}{k}, \omega)$ may be transfered to the left in equation (1). The whole or a part of the modification in the surface impedance matrix $\underset{\approx}{Z}$ introduced by the passive devices may be

transfered to the right in equation (1). Also a mixture of both these transfers may be instituted. Which of these transfers are used is merely a matter of convenience and expedience to the analysis. In particular and in this connection it may be mentioned that if the active device is monitored linearly then, in any case, the ideal active surface drive vector $\underset{\sim}{P}_a(\underset{\sim}{k}, \omega)$ is derived so that $\underset{\sim}{P}_a(\underset{\sim}{k}, \omega) = \underset{\approx}{Z}_a(\underset{\sim}{k}, \omega)\, \underset{\sim}{V}(\underset{\sim}{k}, \omega)$, where $\underset{\approx}{Z}_a(\underset{\sim}{k}, \omega)$ is an *equivalent* surface impedance matrix that is manipulated by the active surface drive vector. In this sense $\underset{\sim}{P}_a$ does not strictly qualify as an *external* drive. [The equivalent surface impedance matrix $\underset{\approx}{Z}_a(\underset{\sim}{k}, \omega)$ should not be confused with $\underset{\approx}{Z}_\alpha(\underset{\sim}{k}, \omega)$, the latter is derived from $\underset{\approx}{Z}$ by setting the surface impedance $Z_{p\alpha}(\underset{\sim}{k}, \omega)$ of the (α)th fluid equal to zero, see equation (3a) versus equation (3b). The use of $\underset{\approx}{Z}_\alpha(\underset{\sim}{k}, \omega)$ will become clear in subsequent discussions.] An equivalent circuit diagram of equation (1) is presented in Figure 2. It is noted that the surface impedances Z_{p1} and Z_{pN} of the fluids are in fact the fluid loadings on the top and the bottom side of the dynamic system, respectively, Z_{pj} with $N>j>1$ are the surface impedances of the panel-like layers, and Z_{cij} ($j \neq i$) are the surface impedances of the compliant-like layers. One of the Z_{pj} with $N>j>1$, specifies the surface impedance of the basic panel in the dynamic system. It is clear that the rank N of the surface impedance matrix $\underset{\approx}{Z}$ is equal to the number of panel-like layers + two (2) for the two fluids. [cf. Figure 1.] It is noted that strictly only the removal of panel-like layers (including the fluids) reduces (by one per panel-like layer) the rank of $\underset{\approx}{Z}$. Moreover, it is noted that active surface drives may be applied only on the surfaces of panel-like layers; in this case a given layer may be either actual or contrived to accommodate a plane at which a specific active surface drive may be applied. It is emphasized that the removal of layers and the interactions among them need to be carefully prescribed and followed; cavalier removals may cause serious damage in the analysis. In particular, it is noted that the removal of a fluid is accomplished by closing the rank of $\underset{\approx}{Z}$ over the row and the column associated with this fluid, the removal of a panel-like layer is accomplished by letting its surface impedance approach zero, the removal of a compliant-like layer, that is placed between adjacent panel-like layers, is accomplished by letting its surface impedance approach infinity, and the removal of a compliant-

like layer, that is placed between non-adjacent panel-like layers, is accomplished by letting its surface impedance approach zero.

The surface impedance $Z_{pj}(\underline{k}, \omega)$ with $N > j > 1$ of a panel-like mechanical layer may be expressed generically in the form

$$Z_{pj}(\underline{k}, \omega) = i\omega M_j(\underline{k}, \omega) + R_j(\underline{k}, \omega) + [K_j(\underline{k}, \omega)/i\omega] \quad ; \quad N > j > 1 \ , \tag{4b}$$

where M_j, R_j, and K_j are positive and real; M_j, R_j, and K_j are the lumped surface mass, resistance, and stiffness of the layer, respectively. One may define a loss factor for this panel-like layer. Using equation (4b), one may define

$$\eta_j(\underline{k}, \omega) = \omega R_j(\underline{k}, \omega)/K_j(\underline{k}, \omega) \quad ; \quad N > j > 1 \ . \tag{5}$$

The surface impedance of $Z_{cji}(\underline{k}, \omega)$ $(j \neq i)$ of a compliant-like mechanical layer may be expressed generically in the form

$$Z_{cji}(\underline{k}, \omega) = [K_{ji}(\underline{k}, \omega)/i\omega]\,[1 + i\eta_{ji}(\underline{k}, \omega)] \quad ; \quad j \neq i \ , \tag{4c}$$

where K_{ji} and η_{ji} are positive and real; K_{ji} is the lumped surface stiffness and η_{ji} is the loss factor of the layer.

RADIATIVE PROPERTIES

The radiative properties of the panel are stated in terms of the radiative field generated by the plane dynamic system under the influence of an external mechanical drive. From equation (1) one may state this radiative field in terms of the pressure $P(\underline{k}, z, \omega)$ on a plane above (z>0) and/or below (z<0) the plane of the basic panel. These pressures may be derived from equation (1) through (4) in the form [1,2]

$$P_\alpha(\underset{\sim}{k}, z, \omega) = Z_{p\alpha}(\underset{\sim}{k}, \omega)\, V_\alpha(\underset{\sim}{k}, \omega) \exp[-i|z|k_{z\alpha}(\underset{\sim}{k}, \omega)] \ , \ \alpha = 1 \text{ or } N \ ;$$

$$P_\alpha(\underset{\sim}{k}, z, \omega) = \begin{cases} P_1(\underset{\sim}{k}, z, \omega) \ , \ z > 0 \\ P_N(\underset{\sim}{k}, z, \omega) \ , \ z < 0 \end{cases} \ , \tag{6}$$

where

$$V_\alpha(\underset{\sim}{k}, \omega) = V_\alpha^e(\underset{\sim}{k}, \omega) + V_\alpha^a(\underset{\sim}{k}, \omega) \ , \tag{7}$$

$$V_\alpha^\gamma(\underset{\sim}{k}, \omega) = \sum_{i=2}^{N-1} Y_{\alpha i}(\underset{\sim}{k}, \omega)\ \varepsilon_\gamma P_{\gamma i}(\underset{\sim}{k}, \omega) \ ; \quad \gamma = e \text{ or } a \ ; \quad \varepsilon_e = 1 \ ; \quad \varepsilon_a = -1 \ , \tag{8}$$

$$\underset{\approx}{Y} = (Y_{ji}) \ ; \quad \underset{\approx}{Y} = (\underset{\approx}{Z})^{-1} \ . \tag{9}$$

The far field (radiative) pressure is stated in terms of the pressure $p_\alpha(r,\theta,\phi,\omega)$, which is expressed in spherical coordinates, see Figure 3. The pressure $p_1(r,\theta,\phi,\omega)$ is the far field pressure above $[0 \le \theta < (\pi/2)]$ and $p_N(r,\theta,\phi,\omega)$ is the far field pressure below $[\pi \ge \theta > (\pi/2)]$ the plane of the basic panel. These pressures may be derived from equation (6) and Reference 2 in the form

$$p_\alpha(r,\theta,\phi,\omega) = p_\alpha^e(r,\theta,\phi,\omega) + p_\alpha^a(r,\theta,\phi,\omega) \ ;$$

$$p_\alpha^\gamma(r,\theta,\phi,\omega) \simeq (i\rho_\alpha\omega)\, V_\alpha^\gamma(\underset{\sim}{\kappa}_\alpha, \omega)\, \psi_\alpha(r) \ ;$$

$$V_\alpha^\gamma(\underset{\sim}{\kappa}_\alpha, \omega) = \sum_{i=2}^{N-1} Y_{\alpha i}(\underset{\sim}{\kappa}_\alpha, \omega)\ \varepsilon_\gamma P_{\gamma i}(\underset{\sim}{\kappa}_\alpha, \omega) \ , \tag{10}$$

where

$$\underset{\sim}{\kappa}_\alpha = \{\kappa_\alpha \cos(\phi), \kappa_\alpha \sin(\phi)\} \ ; \quad \psi_\alpha(r) = (r)^{-1} \exp[-i(\omega/c_\alpha)r] \ ; \quad \kappa_\alpha = [(\omega/c_\alpha)\sin(\theta)] \ ;$$

$$r^2 = |\underset{\sim}{x}|^2 + z^2 \ ; \quad |\underset{\sim}{x}|^2 = x^2 + y^2 \ ; \quad (\omega/c_\alpha)r >> 1 \ . \tag{11}$$

[cf. Figure 3.] It is clear that controlling the far field radiated pressure is directly related to the control of the supersonic part of the spectral velocity distribution $V_\alpha(\underset{\sim}{\kappa}_\alpha, \omega)$ on the surface that is

in contact with the fluid at the top ($\alpha = 1$) or the bottom ($\alpha = N$) of the plane dynamic system. The supersonic designation is with respect to the speed of sound c_α in the irradiated fluid. This control can then be deciphered and evaluated from equations (6) through (8) and (10). These equations are clearly central to the assessment of the quality of the control of the radiative properties that may be achieved by introducing passive mechanical layers and/or active surface drives on the basic panel. It needs to be appreciated that equations (6) through (8) and (10) are satisfied with respect to a specific $\{\underline{k}, \omega\}$. Therefore, the indicated control of one spectral component does not necessarily gurantee the control of another.

Trivial, but instructive, examples of total control can be cited:

1. The surface stiffness K_{12} is rendered equal to zero. In this case

$$K_{12} \equiv 0 \quad \therefore \quad V_1 = 0 \ , \quad P_1 = 0 \ , \quad \text{and } p_1 = 0 \ . \tag{12}$$

2. The active surface drive vector $\underline{P}_a$ is rendered equal to the external drive vector $\underline{P}_e$. In this case

$$\underline{P}_a = \underline{P}_e \quad \therefore \quad V_1 = 0 \ , \quad P_1 = 0 \ , \quad \text{and } \ p_1 = 0 \ . \tag{13}$$

In practice, the conditions that are rendered in the cited examples can hardly be achieved. More realistic examples will be dealt with in subsequent parts to this paper.

REFLECTIVE PROPERTIES

The reflective properties of the panel are stated in terms of the (specular) reflection and the transmission coefficients, $R_{\alpha\alpha}(\underline{k}_\alpha, \omega)$ and $R_{\alpha\beta}(\underline{k}_\beta, \omega)$, respectively, where $\alpha = 1$ or N and $\beta = N$ or 1, respectively. From equations (7) and (8), and with the help of Reference 1, one may derive

$$R_{\alpha\alpha}(\underline{k}_\alpha, \omega) = R^0_\alpha(\underline{k}_\alpha, \omega) + R^a_\alpha(\underline{k}_\alpha, \omega) \ , \tag{14a}$$

$$R_{\alpha\beta}(\underline{k}_\beta, \omega) = R^0_{\alpha\beta}(\underline{k}_\beta, \omega) + R^a_{\alpha\beta}(\underline{k}_\beta, \omega) \quad , \tag{15a}$$

$$R^0_\alpha(\underline{k}_\alpha, \omega) = 1 - 2\, Z_{p\alpha}(\underline{k}_\beta, \omega)\ \ Y_{\alpha\alpha}(\underline{k}_\alpha, \omega) \quad , \tag{16}$$

$$R^0_{\alpha\beta}(\underline{k}_\beta, \omega) = 2\, Z_{p\alpha}(\underline{k}_\beta, \omega)\ \ Y_{\alpha\beta}(\underline{k}_\beta, \omega) \quad , \tag{17}$$

$$R^a_\alpha(\underline{k}_\alpha, \omega) = -Z_{p\alpha}(\underline{k}_\alpha, \omega) \sum_{i=2}^{N-1} Y_{\alpha i}(\underline{k}_\alpha, \omega)\ \overline{P}^\alpha_{ai}(\underline{k}_\alpha, \omega) \quad , \tag{18}$$

$$R^a_{\alpha\beta}(\underline{k}_\beta, \omega) = -Z_{p\alpha}(\underline{k}_\beta, \omega) \sum_{i=2}^{N-1} Y_{\alpha i}(\underline{k}_\beta, \omega)\ \overline{P}^\beta_{ai}(\underline{k}_\beta, \omega) \quad , \tag{19}$$

where

$$\overline{P}^\alpha_{ai}(\underline{k}_\alpha, \omega) = [P_{ai}(\underline{k}_\alpha, \omega) \,/\, P_{I\alpha}(\underline{k}_\alpha, \omega)] \quad ;$$

$$\overline{P}^\beta_{ai}(\underline{k}_\beta, \omega) = [P_{ai}(\underline{k}_\beta, \omega) \,/\, P_{I\beta}(\underline{k}_\beta, \omega)] \quad , \tag{20}$$

The quantity $P_{I\alpha}(\underline{k}_\alpha, \omega)$ is the incident pressure on the surface of the dynamic system in contact with the (α)th fluid and $\underline{k}_\alpha$ is the incidence wavevector

$$\underline{k}_\alpha = \{\kappa_{\alpha\alpha} \cos(\phi_\alpha), \kappa_{\alpha\alpha} \sin(\phi_\alpha)\} \quad ; \quad \kappa_{\alpha\alpha} = (\omega/c_\alpha)\sin(\theta_\alpha) \quad , \tag{21}$$

see Figure 4 [1,2]. The incidence angular designation in the (α)th fluid is $\{\theta_\alpha, \phi_\alpha\}$; a normal incidence in the top fluid is defined by $\theta_1 = 0$. The wavevector $\underline{k}_\alpha$ is, by definition, supersonic with respect to the speed of sound c_α; the incidence is defined in terms of a single plane wave. The control of the reflective properties of the dynamic system can be deciphered and evaluated from equations (14) through (20). These equations are then central to the assessment of the quality of

the control of the reflective properties that may be achieved by introducing passive mechanical layers and/or active surface drives on to the basic panel.

If only passive mechanical layers are introduced, equations (14a) and (15a) reduce to

$$R_{\alpha\alpha}(\underset{\sim}{k}_\alpha, \omega) = R^0_\alpha(\underset{\sim}{k}_\alpha, \omega) \quad , \tag{14b}$$

$$R_{\alpha\beta}(\underset{\sim}{k}_\beta, \omega) = R^0_{\alpha\beta}(\underset{\sim}{k}_\beta, \omega) \quad . \tag{15b}$$

Moreover, from equations (1) through (3) one may show that

$$Y_{\alpha\alpha}(\underset{\sim}{k}, \omega) = [Z_{p\alpha}(\underset{\sim}{k}, \omega) + Z_\alpha(\underset{\sim}{k}, \omega)]^{-1} \quad , \tag{22}$$

where

$$Z_\alpha = (Y_{\alpha\alpha\alpha})^{-1} \quad ; \quad \underset{\approx}{Y}_\alpha = (\underset{\approx}{Z}_\alpha)^{-1} = (Y_{\alpha ji}) \quad . \tag{23}$$

One recognizes $Z_\alpha(\underset{\sim}{k}, \omega)$ as the surface impedance perceived into the boundary of the plane dynamic system that faces the (α)th fluid. In terms of equations (16), (22), and (23), one may cast equation (14b) in the more familiar form

$$R^0_\alpha(\underset{\sim}{k}_\alpha, \omega) = [Z_\alpha(\underset{\sim}{k}_\alpha, \omega) - Z_{p\alpha}(\underset{\sim}{k}_\alpha, \omega)] \; [Z_\alpha(\underset{\sim}{k}_\alpha, \omega) + Z_{p\alpha}(\underset{\sim}{k}_\alpha, \omega)]^{-1} \quad . \tag{14c}$$

Again, it is noted that equations (14) through (20) are satisfied with respect to a specific $\{\underset{\sim}{k}, \omega\}$. Therefore, the indicated control of one component does not necessarily gaurantee the control of another.

As in the preceding section, it may be instructive to cite a couple of trivial examples of total control:

1. The surface stiffness K_{12} is rendered equal to zero. In this case

$$K_{12} = 0 \quad \therefore \quad R^{0}_{\alpha\beta}(\underline{k}_{\beta}, \omega) = 0 \ . \tag{24}$$

2. The active surface drive vector $\underline{P}_a$ is adjusted so that the active reflection coefficient $R^{a}_{\alpha}(\underline{k}_{\alpha}, \omega)$ is rendered equal to the negative value of the passive reflection coefficient $R^{0}_{\alpha}(\underline{k}_{\alpha}, \omega)$. In this case

$$R^{a}_{\alpha} = -R^{0}_{\alpha} \quad \therefore \quad R_{\alpha\alpha}(\underline{k}_{\alpha}, \omega) = 0 \ . \tag{25}$$

Again, in practice, the conditions that are rendered in the cited examples can hardly be achieved. More realistic examples will be dealt with in subsequent parts to this paper.

CONCLUDING REMARKS

The brief review just presented indicates that the formalism is capable of addressing a large variety of issues relating to the active and/or passive control of the radiative and reflective properties of a plane dynamic system consisting of an appropriately stratified panel which is immersed in fluids. The advantage of the present assessment is that the radiative and reflective properties can be estimated under a single analytical mantle. One may then avoid the pitfall in which indicated improvement with respect to the radiative properties may have adverse effects on the reflective properties, and vice versa. However, one is reminded again that the dynamic system here considered is primitive and, therefore, is even phenomenologically limited in scope. The primitive nature of the dynamic system and the limitation in scope of the analysis are largely associated with the assumed spatial uniformity in the plane of the dynamic system so that the complications, that are usually encountered with respect to wavevector conversions (or equivalently spatial scatterings), are suppressed. [cf. Appendix A.] The primitiveness and the limitation can be relieved somewhat in the manner discussed and developed in Reference 1. This relief was instituted in Reference 1 without interfering with the advantage in the formalism just mentioned above.

The material discussed and developed in this paper is intended to serve as the basis for a number of subsequent papers (parts) in which some details and specific issues of this subject matter will be presented.

APPENDIX A

THE RADIATIVE AND REFLECTIVE PROPERTIES OF A MORE REALISTIC STRUCTURE

It may be in order to state the radiative and reflective properties of a more realistic structure so that some of the severe simplifying assumptions that are made in the text can be assessed by inference. The surfaces of the structure that are in contact with the fluid will provide the structure with its radiative and reflective properties. Therefore, the determination of the response on these surfaces, induced by external drives, is crucial. The velocity $v(\underline{x}, t)$ on the structural surfaces, induced by the external drive $p_e(\underline{x}_b, t')$ can be formally stated in terms of the impulse response function $g_s(\underline{x}\,|\,\underline{x}_b, t\,|\,t')$ in the form

$$v(\underline{x}, t) = \int g_s(\underline{x}\,|\,\underline{x}_b, t\,|\,t')\, d\underline{x}_b dt'\, p_e(\underline{x}_b, t') \quad , \tag{A1a}$$

where $\underline{x}$ is a spatial vector variable that spans the surfaces only, $\underline{x}_b$ is a spatial vector variable that may span the entire structure; the span of $\underline{x}_b$ is inclusive of the span of $\underline{x}$ but not necessarily vice versa, and t and t′ are temporal variables. It is noted that g_s converts a pressure drive into a velocity response. The pressure $p(\underline{x}_f, t)$ in the fluid, generated by the velocity $v(\underline{x}, t'')$ on the surfaces of the structure that is in contact with the fluid, is derived in terms of the impulse response function $g_f(\underline{x}\,|\,\underline{x}_s, t\,|\,t'')$ in the form

$$p(\underline{x}_f, t) = \int g_f(\underline{x}_f\,|\,\underline{x}, t\,|\,t'')\, d\underline{x} dt''\, v(\underline{x}, t'') \quad , \tag{A2a}$$

where $\underline{x}_f$ is the spatial vector variable in the space occupied by the fluid. Again, the span of $\underline{x}_f$ is inclusive of the span of $\underline{x}$ but not necessarily vice versa. It is noted that g_f converts a velocity drive into a pressure response. The radiative properties of the structure are defined by combining equations (A1a) and (A2a) in the form

$$p(\underset{\sim}{x}_f, t) = \int g_{fs}(\underset{\sim}{x}_f | \underset{\sim}{x}_b, t | t')\, d\underset{\sim}{x}_b\, dt'\, p_e(\underset{\sim}{x}_b, t') \quad , \tag{A3a}$$

where the impulse response function $g_{fs}(\underset{\sim}{x}_f | \underset{\sim}{x}_b, t | t')$ is for the entire process of converting external drives, in and on the radiating surfaces of the structure, into radiated pressures on the radiating surfaces and in the fluid. It is defined in terms of the impulse response functions g_f and g_s in the form

$$g_{fs}(\underset{\sim}{x}_f | \underset{\sim}{x}_b, t | t') = \int g_f(\underset{\sim}{x}_f | \underset{\sim}{x}, t | t'')\, d\underset{\sim}{x}\, dt''\, g_s(\underset{\sim}{x} | \underset{\sim}{x}_b, t'' | t') \quad . \tag{A4a}$$

It is noted that the span of $\underset{\sim}{x}_f$ and the span of $\underset{\sim}{x}_b$ both include the span of $\underset{\sim}{x}$. If the structure and the fluid do not change with time, the impulse response functions are stationary in the temporal domain and equations (A1a) through (A4a) can be reduced by a Fourier transformation with respect to the temporal variable; namely

$$\tilde{v}(\underset{\sim}{x}, \omega) = \int \tilde{g}_s(\underset{\sim}{x} | \underset{\sim}{x}_b, \omega)\, d\underset{\sim}{x}_b\, \tilde{p}_e(\underset{\sim}{x}_b, \omega) \quad , \tag{A1b}$$

$$\tilde{p}(\underset{\sim}{x}_f, \omega) = \int \tilde{g}_f(\underset{\sim}{x}_f | \underset{\sim}{x}, \omega)\, d\underset{\sim}{x}\, \tilde{v}(\underset{\sim}{x}, \omega) \quad , \tag{A2b}$$

$$\tilde{p}(\underset{\sim}{x}_f, \omega) = \int \tilde{g}_{fs}(\underset{\sim}{x}_f | \underset{\sim}{x}_b, \omega)\, d\underset{\sim}{x}_b\, \tilde{p}_e(\underset{\sim}{x}_b, \omega) \quad , \tag{A3b}$$

$$\tilde{g}_{fs}(\underset{\sim}{x}_f | \underset{\sim}{x}_b, \omega) = \int \tilde{g}_f(\underset{\sim}{x}_f | \underset{\sim}{x}, \omega)\, d\underset{\sim}{x}\, \tilde{g}(\underset{\sim}{x} | \underset{\sim}{x}_b, \omega) \quad , \tag{A4b}$$

respectively, where typically

$$\tilde{p}(\underset{\sim}{x}, \omega) = (2\pi)^{-1/2} \int dt\, p(\underset{\sim}{x}, t) \exp(-i\omega t) \quad , \tag{A5}$$

$$g_f(\underset{\sim}{x}|\underset{\sim}{x}', t|t') \rightarrow (2\pi)^{-1/2}\, g_f(\underset{\sim}{x}|\underset{\sim}{x}', t-t') \quad ;$$

$$\tilde{g}_f(\underset{\sim}{x}|\underset{\sim}{x}', \omega) = (2\pi)^{-1/2} \int g_f(\underset{\sim}{x}|\underset{\sim}{x}', \tau)\, d\tau \exp(-i\tau\omega) \quad . \tag{A6}$$

To derive the reflective properties of the structure the surfaces of the structure are first blocked and the reflected (scattered) pressure $p_{oI}(\underset{\sim}{x}, t)$ is stated in terms of the impulse response function $g_o(\underset{\sim}{x}_f|\underset{\sim}{x}, t|t')$ and the incident pressure $p_I(\underset{\sim}{x}_f, t)$; namely,

$$g_{oI}(\underset{\sim}{x}_f, t) = \int g_o(\underset{\sim}{x}_f|\underset{\sim}{x}, t|t')\, d\underset{\sim}{x}\, dt'\, p_I(\underset{\sim}{x}, t') \quad . \tag{A7a}$$

The pressure on the blocked surfaces is then given by

$$p_o(\underset{\sim}{x}, t) = p_I(\underset{\sim}{x}, t) + p_{oI}(\underset{\sim}{x}, t) \quad . \tag{A8a}$$

The impulse response function g_o converts an incident pressure on the blocked structure into a reflected (scattered) pressure. The reflected (scattered) pressure $p_R(\underset{\sim}{x}, t)$ that is generated by the incident pressure $p_I(\underset{\sim}{x}, t)$ on the in situ structure may be derived from equations (A3a) and (A8a) in the form

$$p_R(\underset{\sim}{x}_f, t) = \int g_R(\underset{\sim}{x}_f|\underset{\sim}{x}, t|t')\, d\underset{\sim}{x}\, dt'\, p_I(\underset{\sim}{x}, t') \quad , \tag{A9a}$$

where g_R is the impulse response function that converts an incident pressure on the structure into a reflected (scattered) pressure. This impulse response function is determined from equations (A3a) and (A7a) through (A9a) to be of the form

$$g_R(\underset{\sim}{x}_f|\underset{\sim}{x}, t|t') = [g_o(\underset{\sim}{x}_f|\underset{\sim}{x}, t|t') - g_{fs}(\underset{\sim}{x}_f|\underset{\sim}{x}, t|t')$$

$$- \int g_{fs}(\underset{\sim}{x}_f|\underset{\sim}{x}', t|t'')\, d\underset{\sim}{x}'\, dt''\, g_o(\underset{\sim}{x}'|\underset{\sim}{x}, t''|t')] \quad , \tag{A10a}$$

where g_{fs} is stated in equation (A4a). Again, if the structure and the fluid do not change with time equations (A7a) through (A10a) can be reduced by a Fourier transformation; namely

$$\tilde{p}_{oI}(\underset{\sim}{x}_f, \omega) = \int \tilde{g}_o(\underset{\sim}{x}_f|\underset{\sim}{x}, \omega)\, d\underset{\sim}{x}\, \tilde{p}_I(\underset{\sim}{x}, \omega) \quad , \tag{A7b}$$

$$\tilde{p}_o(\underset{\sim}{x}, \omega) = \tilde{p}_I(\underset{\sim}{x}, \omega) + \tilde{p}_{oI}(\underset{\sim}{x}, \omega) \quad , \tag{A8b}$$

$$\tilde{p}_R(\underset{\sim}{x}_f, \omega) = \int \tilde{g}_R(\underset{\sim}{x}_f|\underset{\sim}{x}, \omega)\, d\underset{\sim}{x}\, \tilde{p}_I(\underset{\sim}{x}, \omega) \quad , \tag{A9b}$$

$$\tilde{g}_R(\underset{\sim}{x}_f|\underset{\sim}{x}, \omega) = [\tilde{g}_o(\underset{\sim}{x}_f|\underset{\sim}{x}, \omega) - \tilde{g}_{fs}(\underset{\sim}{x}_f|\underset{\sim}{x}, \omega)$$

$$- \int \tilde{g}_{fs}(\underset{\sim}{x}_f|\underset{\sim}{x}', \omega)\, d\underset{\sim}{x}'\, \tilde{g}_o(\underset{\sim}{x}'|\underset{\sim}{x}, \omega)] \quad . \tag{A10b}$$

The simplicity that is attained in the text is largely due to the stationarity that is imposed in the spatial variables as well as in the temporal variable. [cf. equations (A1a) through (A4a) and (A7a) through (A10a) versus equations (A1b) through (A4b) and (A7b) through (A10b), respectively.] Moreover, the span of $\underset{\sim}{x}_b$, in and on the structure, is made to coincide with the span of $\underset{\sim}{x}$. For example, if the surface is chosen plane and uniform, then equations (A7b) through (A10b) may be readily Fourier transformed with respect to the spatial variables, attaining a substantial reduction in the equations expressed in the spectral domain, in analogy to the reduction attained with respect to the temporal domain just derived. The impositions that will produce such reductions are quite restrictive and, therefore, the conclusions drawn from the analysis conducted in the text need be taken sparingly and with caution.

APPENDIX B

A REMARK TO APPENDIX A

Situations may arise in which the scalar equation (A1a) may not be a sufficient description to derive the velocity $v(\underset{\sim}{x}, t)$. In those situations one may have to revert to more elaborate models of the structure in order to derive the velocity $v(\underset{\sim}{x}, t)$ in a vectorial format. In the past, several of these more elaborate models were constructed and formulated. For example, it may be conducive to subdivide the structure into a number of reasonably simple dynamic systems that are coupled. It is then assumed that a procedure can be found for which the impulse response matrix $\underset{\approx}{g}_s(\hat{\underset{\sim}{x}}_b \,|\, \hat{\underset{\sim}{x}}'_b, t \,|\, t')$ for the multitude of coupled dynamic systems may be established [3,4]. In this format

$$\underset{\approx}{g}_s(\hat{\underset{\sim}{x}}_b \,|\, \hat{\underset{\sim}{x}}'_b, t \,|\, t') = \left(g_{sji}(\hat{x}_{bj} \,|\, \hat{x}'_{bi}, t \,|\, t') \right) \quad , \tag{B1}$$

where $g_{sji}(\hat{x}_{bj} \,|\, \hat{x}'_{bi}, t \,|\, t')$ is the transfer conductance between the external drive $p_{ei}(\hat{x}'_{bi}, t')$ on the (i)th dynamic system and the velocity (response) $v_j(\hat{x}_{bj}, t)$ of the (j)th dynamic system [3,4]. In the notations of equation (B1) it is to be understood that

$$\hat{x}_{bj} = \sum_{s}^{S_0} \hat{s}_j \, x_{sbj} \quad ; \qquad d\hat{x}_{bj} = \prod_{s}^{S_0} dx_{sbj} \quad , \tag{B2}$$

where s_0 is the spatial dimensionality of the (j)th dynamic system and $\hat{s}_j$ is a unit vector defining a single spatial coordinate in this dynamic system [3]. In the formalism of this procedure one may state that the velocity $v_j(\hat{x}_{bj}, t)$ of the (j)th dynamic system is

$$v_j(\hat{x}_{bj}, t) = \int \sum_{i} g_{sji} \, (\hat{x}_{bj} \,|\, \hat{x}'_{bi}, t \,|\, t') \; d\hat{x}'_{bi} \, dt' \, p_{ei}(\hat{x}'_{bi}, t') \quad , \tag{B3}$$

Assigning a group of dynamic systems that collectively represent the structural surfaces that are in contact with the fluid, one may state formally that

$$v(\underset{\sim}{x}, t) = \sum_j^J v_j(\hat{x}_{bj}, t) \quad ; \qquad \underset{\sim}{x} = \sum_j^J \hat{x}_{bj} \quad , \tag{B4}$$

where J designates that group of dynamic systems. From equations (B3) and (B4) one obtains

$$v(\underset{\sim}{x}, t) = \sum_j^J \int \sum_i g_{sji}(\hat{x}_{bj} \,|\, (\hat{x}'_{bi})\; d\hat{x}'_{bi}\, dt'\, p_{ei}(\hat{x}'_{bi}, t') \quad . \tag{B5}$$

Indeed, in this vectorial format, equation (A1a) may be considered a shorthand representation of equation (B5). The amendments that are necessary in Appendix A to accommodate equation (B5) are merely procedural. Other variations on the theme just proposed may be devised and developed to suit particular situations [3,4]. As in this Appendix, however, such considerations lie outside the scope of even Appendix A.

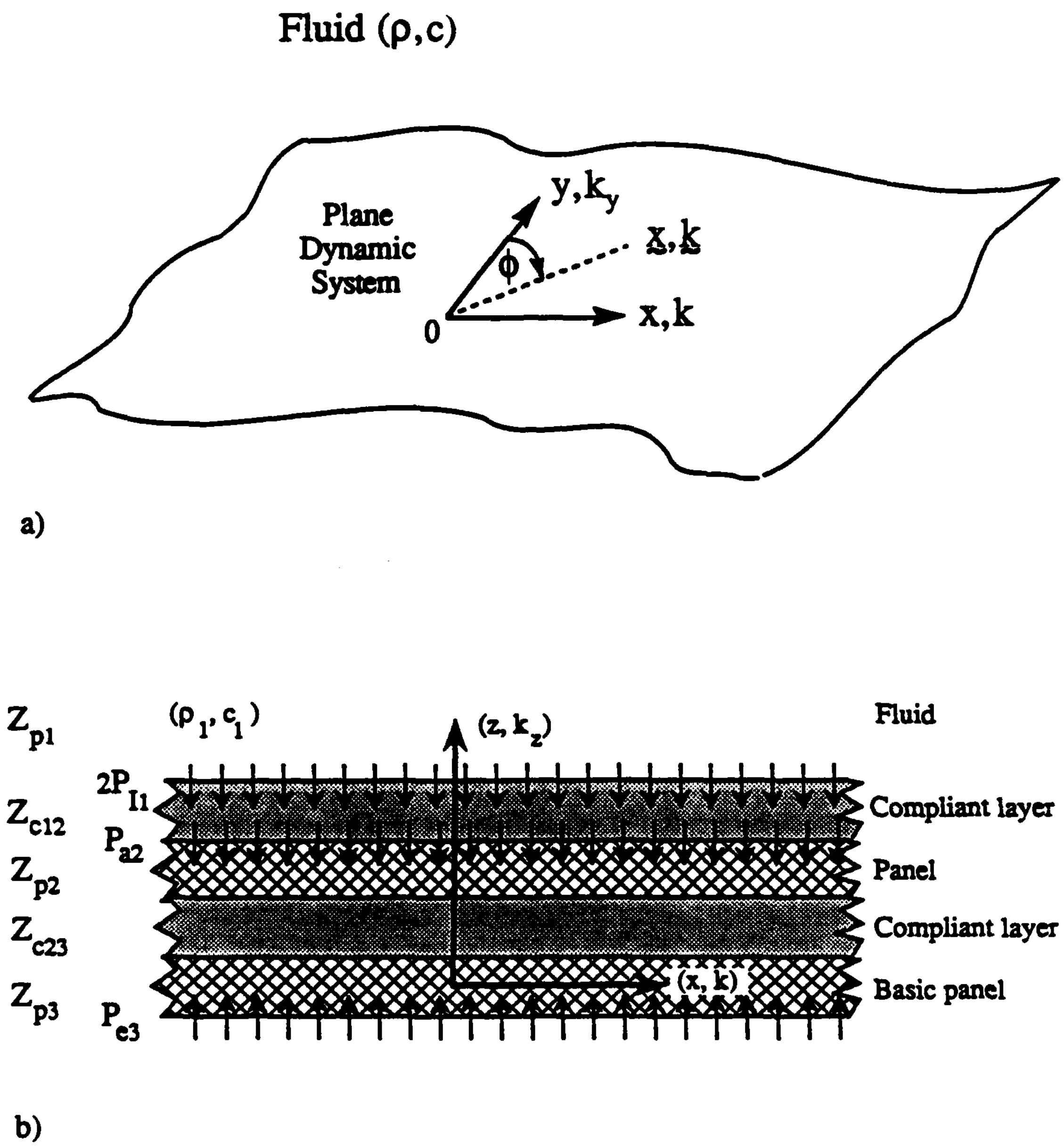

Fig. 1. Plane dynamic system and coordinate system.
(a) Top view.
(b) Typical configuration showing top fluid, passive mechanical layers stratified to the basic panel, the active surface drive, the external drive and the incident blocked drive.

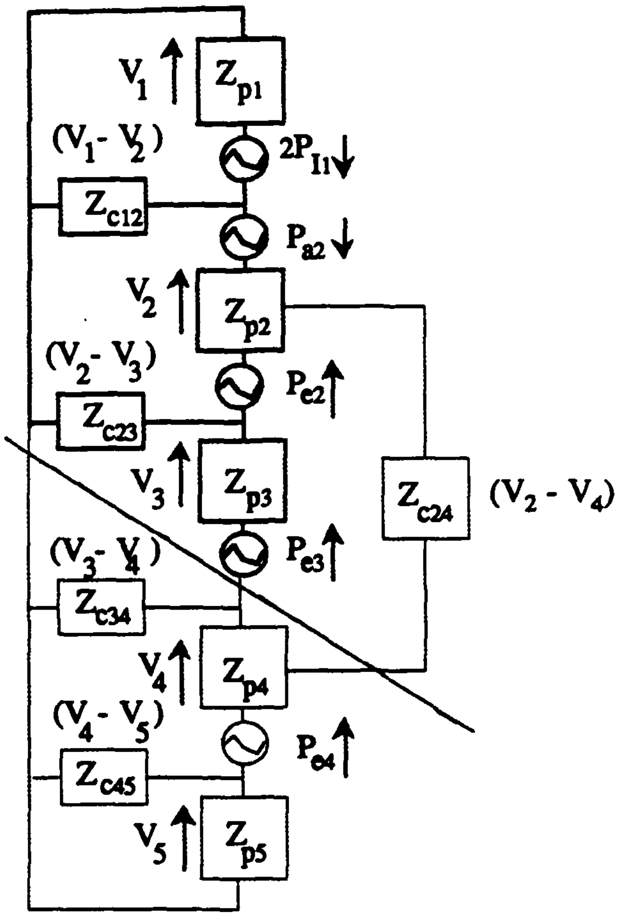

Fig 2. Equivalent circuit diagram of equation (1) and Figure 1b, and more.

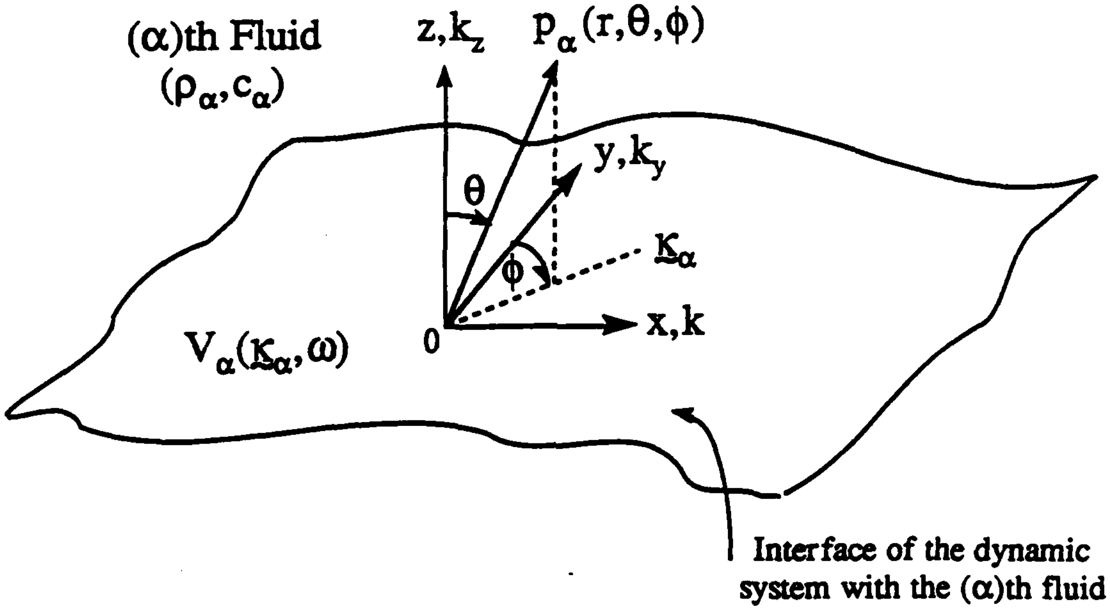

Fig. 3. Spherical coordinate system for evaluating the far field radiated pressure, $p_\alpha(r, \theta, \phi)$.

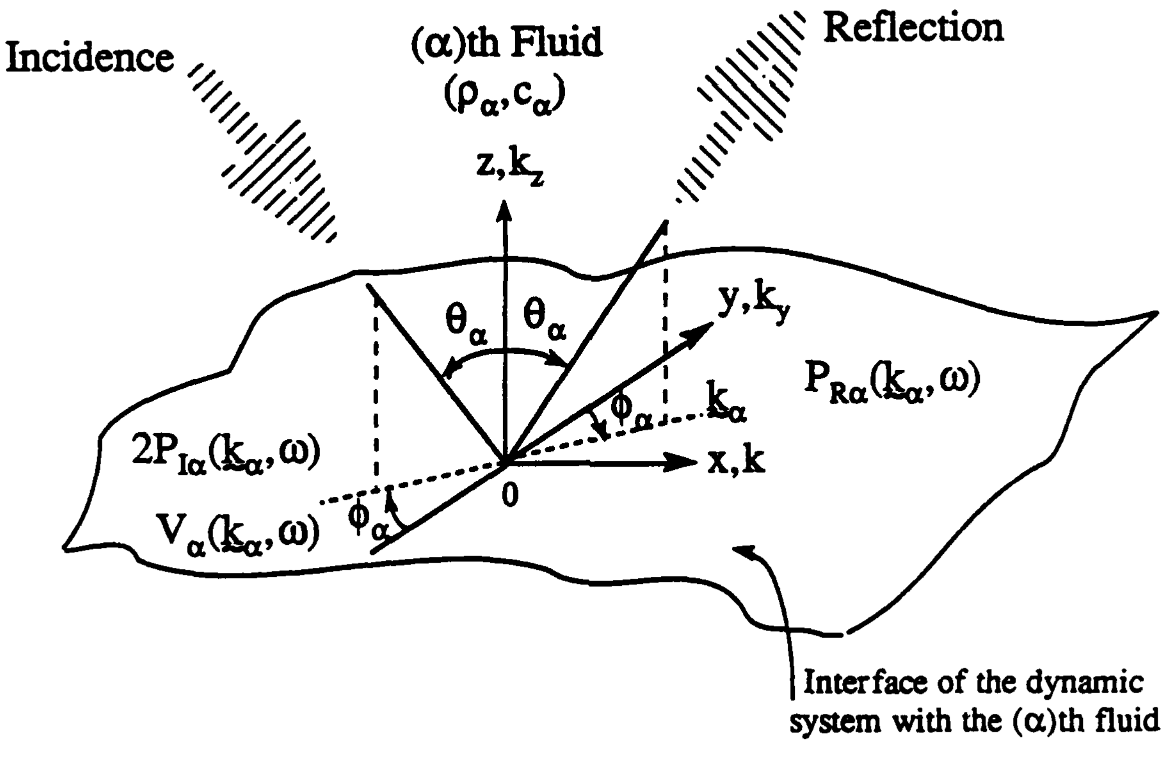

Fig. 4. Incident pressure $P_{I\alpha}(k_\alpha,\omega)$, specularly reflected pressure $P_{R\alpha}(k_\alpha,\omega)$, and velocity $V_\alpha(k_\alpha,\omega)$ on the interface between the (α)th fluid and the plane dynamic system.

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